NUSL White Paper: An Ultra Low Background Counting Facility

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February 12, 2002

1 Introduction

As part of an initiative to build a National Underground Science Laboratory (NUSL), it is imperative that one must outfit any such laboratory with a state-of-the-art low background counting facility. Many of the scientific projects planned for NUSL, e.g. solar neutrino, double beta decay, and dark matter experiments, have a common denominator: the need for extremely low activity materials. This common need for sensitive counting resources is necessary for experiments where natural, man made, and cosmogenic activities may contribute to the detector background and therefore interfere with the physics measurement. The full benefit of the large overburden, thus eliminating the cosmic ray induced backgrounds, can only be utilized if these material related interferences are eliminated as well. For this reason the investment into new scientific projects must be accompanied by the creation of a central screening site to ensure their scientific impact. Such a focussed approach would, to some extent, avoid multiple investments into local screening facilities, which undoubtedly will be requested when the new projects go into the construction phase.

In addition to the material screening needs of large scale physics experiments, a low background facility should be available for a broad spectrum of users. A few such potential uses include fabrication of ultrapure materials for commercial purposes, monitoring trace radioactive elements in the environment, measuring activity in silicon wafers for semiconductor manufacturing, and serving national nuclear nonproliferation needs. The requirements for these endeavors have much in common with the screening of materials for fabrication purposes but may also have special demands that should be considered during the design phase of any facility.

1.1 Overview of Low Background Counting

Traditionally, low background gamma ray spectroscopy using Ge detectors served as the prime tool for material selection. Sensitivities down to few hundred ppt of U and Th are routinely achieved using commercially available detectors. Such detection limits will suffice for the bulk of the technical construction components, even for the most demanding applications. As examples, we cite publications detailing the material selection for the SNO [1] and Borexino [2] solar neutrino experiments. High sample through-put (equivalent to the availability of multiple counting stations) and good diagnostic power are needed to fulfill this task. More sophisticated Ge detectors can probe even the few ppt domain. Ge counters also serve as the counters for neutron activation analysis, which has played an important role in many low background experiments.

In the US, Lawrence Berkeley National Laboratory operates a underground counting lab inside the Oroville dam. This facility is now more than 15 years old, and it is not clear how to modernize it in order to reduce the background further. Pacific Northwest National Laboratory has operated Ge detectors in various underground locations. No dedicated counting site exists in the USA which is accessible to the broader scientific community. In addition, various university groups and national laboratories perform low background counting either above ground or at very shallow sites [3]. We note that no coordinated effort among the facilities exists at this point.

The new generation of experiments will require material testing which is a factor 100 or even 10000 more sensitive than what can be done with existing Ge detectors. The construction of what may be termed a "next generation" counting facility, utilizing large plastic scintillators shielded by a water tank or a large liquid scintillation detector modelled on the Borexino collaboration's Counting Test Facility at Gran Sasso, could serve these needs.

Such a facility would serve as a basis for the technical development of new scientific projects and help to move the US low energy neutrino science to the cutting edge. It is therefore one of the main priorities in order to ensure the highest scientific impact of NUSL.

The applications of ultra sensitive counting techniques cover a much wider spectrum of topics. To elaborate on this in a little more detail, we list ongoing or planned research projects requiring ultra sensitive counting capability as they were presented at the *Conference on Underground Science* (Lead, SD October 2001).

1.2 Topics from the *Conference on Underground Science*

The European Underground Laboratory HADES (Mol, Belgium at a depth of 225 m in clay) is assaying a large number of human lung-tissue samples by means of low background counting. These had been collected in German uranium mining areas with the goal of correlating the activity content with cancer mortality. The same lab assessed the exposure of the public to fast neutrons around the accident site at the Japanese Tokai-mura nuclear fuel processing plant. This was done by assaying neutron activation products in metal spoons which had been collected locally around the accident site. These measurements have been performed using low background Ge detectors. Typical counting sensitivities required for these applications are of the order mBq/kg or ppb for U/Th.

Los Alamos National Laboratory has worked together with the semiconductor manufacturers to understand how surface activities can influence the soft error probability in highly integrated circuits. Reduced counting background would result in greater sample throughput and ultimately aid in improving the competitiveness of their products.

The PIsCES (Precision Isotope Counting Experimental Setup) of the US Navy Research Laboratory aims at the ultra sensitive detection of nuclear fission products. Applications range from verification of compliance with the Comprehensive Test Ban Treaty to nuclear non-proliferation studies and tracking the location and use of nuclear materials for the International Atomic Energy Agency. The proponents of this project envision the use of ultra sensitive Ge detector counting, gas proportional counting, and neutron activation analysis [4].

The diverse nature of the charge for this facility will require a variety of different detection techniques to suit all users. In the following sections we will discuss different detection techniques and try to outline a possible initial instrumentation of this facility. This will be followed by an assessment of the minimal infrastructure requirements needed to make this a successful effort.

2 Techniques of Low Background Counting

2.1 Ge Detector Counting

Low background gamma ray spectroscopy using Ge semiconductor detectors is a well-developed and mature technology. A number of technical publications exists (see Ref. [6]) and ultra low background detectors are commercially available. The outstanding energy resolution gives these detector high diagnostic power. This makes them an excellent choice for counting applications where radioisotope identification is important. All current generation solar neutrino, dark matter and double beta decay experiments have been relying heavily on this detection technique [1, 2].

An array of four such detectors could be set up very quickly as a first stage of the counting lab. Costs involved are generally rather modest. A counting system which has sufficient sensitivity to detect activities around 1 mBq/kg (the equivalent of 80 ppt ^{238}U or 250 ppt ^{232}Th assuming secular equilibrium) would typically be composed of a large Ge detector equipped with a low activity cryostat, an inner sample box made of high purity Cu (about half a ton), and an outer shield made of low ^{210}Pb lead bricks (about 5-10 tons). The sample chamber should be designed to allow the assay of large samples in order to optimize the sensitivity. Environmental radon is usually displaced with boil-off nitrogen from the detector dewar. In a later stage, after a high purity nitrogen gas supply has been installed in the lab, one would make use of its lower Rn content to further improve the detector background. Typical counting times for a 10 kg sample are on the order of 2 weeks per sample to achieve the required sensitivity. At the overburden discussed for NUSL a cosmic ray veto system will not be needed. Read-out electronics are comparatively simple and commercially available. A HV-power supply, high quality amplifier, and a resident data acquisition card would suffice for most applications.

In several above ground counting facilities, Ge detectors that have automatic sample changers are in use. This feature allows them to assay more efficiently a large number of samples. Such a system could easily be developed to accommodate a low-background environment through some straightforward modifications, such as using low-background materials in the sample changers and holders, maintaining a large separation between samples, etc. One would not achieve the best sensitivity levels, but for many applications, it would be adequate and could greatly improve the throughput when measuring a large number of samples.

The main limitation for the sensitivity of these devices is the comparatively poor detection efficiency (a few percent, depending on the gamma ray energy). Such detectors would not necessarily need to be placed at the deepest mine level. However, it may prove advantageous to concentrate all material characterization in one lab in order to simplify detector operation. Different detectors could share the staging area needed to prepare the samples for counting. A staged counting approach in which samples are first pre-screened by Ge counting before the unique and expensive high sensitivity setup (described below) is committed could help to maximize sample throughput. Here the “one lab approach” would offer the clear advantage of not having to move the samples from one lab to another with the associated contamination risk. The development of a multiple Ge detector array, offering higher counting efficiency, could be a straightforward and economical next step in improving counting sensitivity yet maintaining spectroscopic information.

Even after careful material selection the detector background is typically composed of a mixture of primordial and cosmic ray induced activation products in the metal parts of the device. For next generation of Ge detector stations, one could envision using the existing detectors to screen materials for low primordial activity content and to store and machine cryostat parts underground to prevent the build-up of cosmogenic activities in the materials used. This opens the potential for further development towards lower detection limits. An underground machine shop and cleaning area would be needed. Counting sensitivities much below the ppt level for U/Th might not be attainable even at the lowest background due to the limited counting efficiency of Ge detectors.

2.2 Neutron Activation Analysis

If the mission of the proposed lab is defined in a wider sense, one could envision it as a center for trace element analysis. Neutron Activation Analysis (NAA) offers (in its most sophisticated form) sensitivities of 10^{-16} g/g for U/Th [5] for suited materials. As this technique also requires low background counting, it would be a logical choice to provide facilities at NUSL to perform NAA. Shipment of samples irradiated at US research reactors can be arranged in a time scale of 2 to 3 days. For many longer lived activation products (e.g. for ^{238}U and ^{232}Th: ^{239}Np $t_{1/2}$=2.36 d and ^{233}Pa $t_{1/2}$=27 d), it still suffices to take advantage of the favorable counting environment of NUSL and not be hampered by the shipping delay and resulting source decay. Since source related backgrounds (side activities) are an important consideration, high detector resolution is critical.

For the counting itself Ge detectors with a moderate background would suffice. To take full advantage of the favorable counting environment, NUSL should provide an above ground chemical processing laboratory space where radiochemical separation can be performed to suppress source-related backgrounds. Even after post-irradiation processing, these samples are usually composed of a mix of different radioisotopes and are to be considered open sources with all the associated contamination concerns. Without such capability, there is no advantage to counting underground.

The low background Ge detectors used for counting them do not need to have the ultimate level of sophistication as the devices used for direct counting. They should have the best possible energy resolution and peak-to-Compton ratio to suppress side activities that may interfere with analyzing the isotope of interest. A separate group of two Ge detectors should be made available for NAA studies in order to avoid contaminating the low background detectors. One of them should be a planar detector optimized for counting low energy photons. The costs associated with these set ups will be somewhat less than for the ultra low background detectors.

As timely counting is essential to achieve good sensitivity, the counting resources need to be well managed and counting time needs to be reliably assigned well in advance. This places some management burden on the lab personnel.

From the point of view of contamination control, these detectors would ideally be sited in a separate room. Further study will be needed to decide whether or not a separate prefabricated building inside the low background laboratory would be sufficient. This would still allow use of the common infrastructure and would ease detector maintenance for the lab personnel. These issues will have to be balanced against the need for vigorous background control. If separate counting labs will be operated at different overburdens, these set ups can definitely be sited at the shallowest depth.

2.3 Advanced Counting Methods

The next generation low background experiments (solar neutrino, dark matter and double beta decay) will need to reach background levels that are far below what can be screened for even in the best Ge counters. To achieve these levels a variety of screening techniques will be employed, including specialized use of "chemical" methods such as mass spectrometry and NAA to check for certain radioactive isotopes. These techniques, while powerful, do not provide an ultimate check on the total activity from all isotopes in the material, including short-lived isotopes which are essentially impossible to detect chemically. An advanced direct counting screening technique with orders of magnitude improvement sensitivity would therefor be extremely important for essentially all next-generation low background experiments. For the case of experiments based largely or purely on advances on material purity, such screening would play an essential enabling role.

Two different ideas for such an advanced screening facility were presented at the *Conference on Underground Science*. Both are "full body" counting facilities using liquid scintillator. The first idea involves a large water tank, 12 m diameter and 9 m deep, containing 6 counting modules. Each module is an acrylic sample box, with the walls of the box containing liquid scintillator. The box is submersed deep in the water, which serves as a shield, with a minimum thickness of 4 m to the cavern walls. Light guides, which also are the structural support for the sample box, carry light to external PMTs. The sample volume is 0.5 m^2, and the estimated sensitivity, for a plastic, is better than 1 ppt U and Th. The water tank also could serve as a ready-made shield for prototype experiments. This scheme has the advantages of low cost, 1-2 order of magnitude sensitivity improvement over current Ge counters, and large sample volume. The information on the sample is limited to the total count rate. This water tank could also serve as a ready-made shield for up to 3 prototype experiments with 1 m^3 volume. Each would have 4 m of shielding of the cavern walls, and 2 m between adjacent experiments.

A second approach is a small-scale version of the Borexino experiment. Here the sample is immersed in a liquid scintillator volume (protected from the scintillator by a thin plastic layer, if need be). The shielding material is quenched scintillator, separated from the active counting scintillator by a thin, non-structural nylon vessel. An array of PMTs attached to a stainless steel sphere measures the signals, and the whole (diameter of 5-7.5 m) is surrounded by a water shield. Several cylindrical samples with a mass (for metals) for several 100 kg could be measured for 1 month with negligible background, resulting in a sensitivity limit of 10^{-15} g/g U and Th. This is some 3-4 orders of magnitude beyond what is currently achievable. It's advantages are very high sensitivity, modest spectral information, the ability to distinguish surface from bulk contamination, and the ability to distinguish gammas, betas and alphas. The cost of such a system would be higher than for the first idea. Some middle ground between the two proposals may be possible, with a water shield used for a Borexino-like detector.

A final advanced counter discussed at the *Conference on Underground Science* was a wire chamber designed to measure surface activity on samples as large as 1 m^2. Alpha activity from the U and Th chains could be screened at better than the 10^{-12} g/g level. High sensitivity could also be achieved for betas.

3 Infrastructure Requirements

The infrastructure required to build, operate, and further develop the Ultra Low Background Counting Facility at NUSL depends to a large extent on details regarding specific designs which are not well established at this time. We note that as a more concrete view of the laboratory takes shape, the infrastructure requirements will become more apparent. Regardless, there are some features that should be incorporated independent of the exact details of the facility. In the following list we summarize some of common views that were agreed upon at the *Conference on Underground Science.*

- The facility should be large enough to house the suggested initial complement of detectors, allow for future expansion, and be able to accommodate a number of user operated experiments. A room 16 m wide, 50 m long, and 17 m high appears reasonable. Serious consideration should be given as whether two separate chambers are preferred to a single, large chamber. One room could be reserved for the more sensitive counting apparatuses while the other would have less stringent requirements and could contain areas for sample staging and preparation.

- To maintain detector background, the lab should be a clean area. A class 1000 clean room level seems both financially reasonable and sufficient. The lab should provide a mobile "mini-clean room" (e.g., a tent on wheels equipped with HEPA filtration) which can be moved over the Ge detector set ups whenever they have to be opened for sample change. This would allow one to achieve locally class 100 cleanliness whenever required. At its entrance the lab has to provide a change area for the users and cleaning station for the samples. This is important to separate effectively the dirty mine shafts from the lab areas.

- Room temperature and humidity should be well controlled (temperature ± 1 °C). Regulated stable power should be maintained through uninterruptable power supplies. Some consideration should be given to line filtering and shielding from radio frequency interference. The lab should be equipped with sufficient telephone and fast computer connections.

- A sample staging area of at least class 100 quality is needed to prepare samples for counting. This chemical laboratory needs several fume hoods and allow to use and dispose of acids and organic solvents. A high purity water supply will be needed to perform sample cleaning.

- A supply of pressurized, Rn free nitrogen gas is needed to dry samples after cleaning. In the beginning boil off N_2 from a large LN_2 tank would suffice, later to be replaced or augmented by extremely Rn pure N_2. Also useful would be cleaning technologies and surface and liquid cleanliness measurement techniques that are widely used in industry.

- The laboratory needs to be well ventilated (at least one volume exchange per hour) to assure a low ambient Rn level and to effectively removed boil-off nitrogen. Basic reduction for large volumes would come from having adequate ventilation with surface air. In many cases, in localized regions, further reduction from a Rn-scrubbing system would be desirable. Such technique has been developed at Princeton and is used in their clean room. Requirements on the gas tightness of the individual detectors would be eased and plate out of Rn daughters on the sample during installation could be minimized. Finally, these low Rn levels in N_2 and air need to be measured with systems utilizing the pre-concentrating techniques developed for both Borexino and SNO.

- The room should be equipped with an overhead crane serving all measuring stations. This is especially important for the large counting facility which will achieve its enhanced sensitivity though the use of very large samples. Safe sample handling will require an adequate margin of safety be built into the design.

- Underground machining and electroplating capabilities would allow one to minimize the exposure of materials to cosmic radiation and minimize the risk to introduce unknown activation products into the material once they have been characterized underground.

- Sensitive fire and smoke detection systems along with a fire distinguishing system will be needed, particularly if large amounts of flammable liquid scintillator is to be used.

Lastly, we note that one recommendation from the Lead conference was the formation of a consortium of people and institutions that would participate in the development of a low background facility. The way to establish the best facility with the broadest spectrum of capabilities was to draw on the experience of those who have engaged in low-background counting in recent years. The interested parties in this consortium would have the charge of taking this broad outline and producing detailed plans for the layout of an Ultra Low Background Facility.

4 Conclusion

A surprisingly diverse spectrum of applications, ranging from basic physics research and life sciences to national security related issues, would clearly benefit from a central, state-of-the-art counting facility. In all cases cosmic radiation is an important background, and hence a deep underground laboratory would therefore be beneficial to all. NUSL will be freely accessible to all interested users and should be designed at the outset as a multipurpose facility. It will provide a stimulating intellectual environment paired with the most advanced low-background technology. This combination will surely spawn a variety of new and interesting applications and scientific discoveries. In creating such an Ultra Low Background Counting Facility we have the rare opportunity to make use of interdisciplinary cooperation to promote both science and technology. The Ultra Low Background Counting Facility at NUSL could serve as a unique platform to further the wider application of methods originally developed for basic science and bring them to good use for the society as a whole.

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